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CHARACTERISTICS, TREATMENT AND USES OF HIGH-SPEED TOOL STEEL.

I. Development. The history of the cutting of metals with steel tools is characterized by three well defined stages each of which represents an efficiency in rapid cutting operations greatly superior to its predecessor. The first stage, that of the use of the simple carbon tool steel, ended with the discovery by Mushet (about 1870) of his air-hardening steel, which was a high carbon steel containing tungsten with manganese or chromium or both. Mushet's steel was superseded in the third and present era by a low-carbon steel with a tungsten content two to three times as great and containing also chromium. This steel was developed along with the high heat treatment discovered by Taylor and White (about 1900). Shortly after this important step (about 1905), vanadium was introduced in the steel as a relatively large addition and with a considerable increase in its efficiency. The resulting product is now called modern high speed steel.

The principal steps in the development of the lathe tool steels up to 1906 are illustrated by the following extracts from Taylor's data:

Date of Test	Composition C	Mn	Cr	W	V	Cutting Speeds Medium Steel Forging	Hard Steel Forging	Hard Cast Iron	Remarks
1894	1.05	0.19	----	---	---	16 ft.	6 ft.	15 ft. 6 in.	Jessop Carbon steel.
1898	2.40	1.90	0.49	5.62	---	26 ft.	8 ft. 6 in.	28 ft.	Mushet (self-hardening)
1896	1.43	0.23	1.86	8.40	---	61 ft.	19 ft.	39 ft.	Bethlehem (self-hardening)
1906	0.74	0.06	3.86	16.2	---	91 ft.	40 ft.	50 ft.	High-speed steel.
1906	0.68	0.07	5.95	17.8	0.32	99 ft.	41 ft. 6 in.	52 ft.	" " "

3/16 in. depth of cut; 1/16 in. feed; duration of cut 20 minutes.

II. FUNCTION. High-speed tool steel is used, as its name implies, for cutting metals and materials at high speeds with heavy cuts usually far in excess of those possible with carbon or finishing steels. The peculiar property which makes this possible is called "red-hardness" as the cutting surface may become heated to a dull red without impairing its cutting power. Its ability to make heavy cuts at high speeds renders it invaluable for quantity production. Besides being used for roughing operations, it is used to a great extent in tools for finishing where "red hardness" is not so important, but hardness (in the sense of resistance to wear) and capacity for uniform hardening in large pieces is very essential. In fact the tendency to use high speed steel for almost every kind of cutting operation is probably carried to extremes.

III. COMPOSITION. Modern high-speed steel is a high alloy steel, the essential alloy contents of which are within the following limits: carbon (0.50-1.00%), tungsten (12-20%), chromium (1.5-6%) and vanadium (0.5-2.0%). Other elements are of course always present as impurities or additions. While a number of compositions within the limits mentioned will furnish equally good steels, it does not follow that any combination within those limits will. The combinations found best by experience are placed on the market by the steel makers under trade names, all of which come within limits noted above and each of which is supposed to come within certain narrower limits as to composition.

The following analyses are given by Mathews as representative of well-known commercial steels with their relative efficiencies as determined by Taylor's cutting test:

Efficiency %	C %	Si %	Mn %	Cr %	W %	V %
100	0.63	0.27	0.31	2.99	16.87	0.85
70	.64	.22	.24	5.35	18.99	.15
66	.61	.19	.36	3.34	16.28	.40
45	.63	.19	.26	4.21	13.10	.25

They do not represent as wide a variation in carbon as is often found. The following analyses made at the Bureau of two standard steels show a considerable difference in carbon as well as other elements.

%C	%Si	%Mn	%Cr	%W	%V
0.77	0.47	0.25	3.47	17.8	0.74
.56	.20	.42	2.21	13.8	.98

From the high-tungsten and other alloy content it is apparent that the price is very high. It is therefore in the interest of the user to give this steel the most careful and effective treatment possible.

IV. SPECIAL FEATURES. High-speed steel has several unusual characteristics peculiar to it which are intimately connected with its treatment and utility.

(1) High-Temperature Treatment. It must be heated for hardening to an excessively high temperature, such as would ruin simple steels, to obtain its best properties. This treatment necessitates somewhat special equipment for producing the desired heat treatment conditions.

(2) Red Hardness. After being given the high-temperature treatment, it will not lose hardness on tempering until heated above a dull red heat. This is its most valuable characteristic, and its superiority over carbon tool steel, for cutting where high temperatures will be developed, may be clearly seen from the fact that the carbon steel begins to lose hardness appreciably on tempering at 200 degrees C while for high-speed steel the loss begins at about 700 degrees C. Such temperatures for a given loss in hardness indicate roughly the red hardness quality.

(3) Secondary Hardening. The hardness of high-speed steel may be increased over that resulting from the high temperature heat treatment by tempering within certain temperature limits which are relatively high. This property is made use of to obtain slightly higher lathe efficiency and to relieve hardening stresses.

(4) Self-Hardening. High-speed steel has the characteristic of hardening on cooling in air. This feature is important as it permits the uniform hardening of large tools and the use of less drastic quenching media than required for some tool steels. The chromium content is probably responsible in a large degree for this characteristic, though some of the other elements undoubtedly contribute to it.

V. EFFICIENCY TESTS. The test usually employed for determining the efficiency of a given tool steel is that developed by Taylor for lathe roughing tools and consists of determining the cutting speed, other variables being constant, for which the steel will fail or be ruined in 20 min. Taylor measured the time from start until the tool was ruined, that is, the point completely worn off.

Present testing practice is to take the time at which the tool fails, that is, loses its edge and a glaze appears on the metal being cut, for this gives a sharper end point, more consistent results and the tool may be more readily reground. The lathe test is often used to determine the efficiency of a steel for cutting conditions radically different from those in the lathe test and while in this case a fair estimate of its efficiency may be had, the final criterion must of course be its behavior under conditions approximating those of actual operation.

On account of the expense of the lathe or other full size tests to destruction, experiments have been conducted to find if possible a relation between the cutting efficiency and some simple and quick test on the hardened steel. No such relation has been found for hardness, microstructure and magnetic properties. This is obvious from the nature of the property in question, that is, resistance to softening by tempering. Any test of this character will have to be made on the steel tempered above the secondary hardening range so that the progressive loss in hardness, or a parallel property, can be measured and compared for different steels. The value of this test is yet to be determined.

VI. HEAT TREATMENT. It is essential to heat high-speed steel very slowly to a cherry red, about 750 degrees C (1382 degrees F), before heating to a higher temperature in order to prevent cracks and checks. Above this temperature it may be heated as rapidly as desired.

Forging is best carried out at a relatively high temperature, not below 1000 degrees C (1832 degrees F). Cooling from the forging temperature should be slow enough to prevent hardening, otherwise cracking is likely to occur. Hardening (cooling in air or a faster medium) produces a maximum hardness and accompanying brittleness when starting from the forging temperature range, hence the tendency to crack. It is therefore well to cool in the heating furnace, in lime, ashes or any medium which will retard the cooling rate sufficiently. This phase deserves particular attention as cracks formed in the process of forging are very likely to remain indistinguishable until grinding, the fault there by being attributed to the subsequent operation.

For hardening, the heating of high-speed steel demands a very high temperature (1200-1300 degrees C or 2192-2372 degrees F), which is just short of fusion. The production of such temperatures requires somewhat special equipment which, in the form of gas and oil fired furnaces, is placed on the market under the caption High-Speed Steel Furnaces. These furnaces often have an accessory heating unit for preheating.

For work in which the preservation of the surface is no object such as roughing tools the hardening temperature is often judged by Taylor's method of heating until the surface fuses. This is, however, impossible in the case of shaped tools and pyrometric control is then essential.

Platinum thermocouples are necessary for measuring the high temperatures involved and should be well protected by porcelain tubes. Optical and radiation pyrometers may also be used, but their inherent disadvantages must be considered in applying them to production work.

Time of holding at a given temperature is as important as the temperature, so that for efficient production, the pyrometer should be supplemented by a clock, the time and temperature for a given tool and composition being specified to the hardener.

Protection of the surface is always desirable and in some cases may effect a considerable reduction in machine work. It may be prevented in the furnace to a large extent by heating with a yellow flame or packing in a carbon mixture. Some oxidation will, however, occur on transference of the tool from furnace to quenching bath. Oxidation from this source may be prevented to some extent by heating in barium chloride or, by covering the tool with a paste such as is used by file makers. In general slightly carburizing conditions are essential or a very short exposure at the high temperatures.

High-speed steel is essentially an air-hardening steel when used in small sizes, but is generally quenched in oil probably to avoid oxidation while cooling. Quenching in water at ordinary temperatures will almost invariably crack the steel, but water at 100 degrees C will probably give as good results as oil. Quenching directly in a lead or salt bath at the desired tempering temperature reduces the liability to quenching cracks.

It is generally recognized now that the best results are to be obtained by tempering for maximum hardness, i. e., in the temperature range 550-620 degrees C (1022-1148 degrees F). The effect of tempering for secondary hardening is to increase slightly the cutting efficiency as measured by the Taylor 20 minute lathe test, but for shop cutting speeds its beneficial effect is undoubtedly magnified, initial hardness then being of greater value.

For tools requiring constancy of dimensions, tempering is necessary as otherwise heating in service will produce changes in size.

VII. CAST HIGH-SPEED STEEL. Many attempts have been made to avoid waste in machining by casting to shape. It is quite possible to make even intricate castings successfully, but there are several difficulties which limit its development. It is first of all necessary to refine the coarse casting structure and this is most readily done by forging or other hot working. As casting to shape precludes hot working the refining must be done by some other method. Proper annealing will accomplish this, but whether to as satisfactory a degree as forging remains to be determined. In making castings there is always waste in the gate and risers which non-useful metal, in the case of small castings, may be greater than the shape being cast. This method will therefore probably find its most profitable application only in the production of large or specially shaped tools.

VIII. SUBSTITUTES. The high price of high-speedsteel has brought forth a host of substitutes, most of which replace tungsten with chromium or molybdenum in the presence of one or more other alloying elements. These are inappropriately called high-speed steels for their efficiency is much less than that of the high-tungsten high-speed steel, but they evidently have a field of usefulness. For finishing work or intermittent cutting where a high degree of "red hardness" is not so essential, they may compete favorably on a price basis with the high tungsten tools which are regularly used. It must be remembered also that they may require a different and more exacting treatment than the high tungsten steels.

Besides the steel substitutes there are non-ferrous alloys which may be considered as substitutes and are very successfully used in competition with high-speed steel for certain classes of work, particularly for cutting very hard material and for roughing. They are brittle and therefore cannot be used where subject to shock and must be used in short lengths. Tools must be ground to shape and no heat treatment is possible or necessary.

The principal alloys of this class are sold under the trade name of stellite. They are binary, ternary or quaternary alloys composed of either cobalt or nickel and metals of the chromium group, which group includes chromium, tungsten, molybdenum and uranium; the latter, however, has not been used commercially in the alloys. The Stellite alloys may be broadly divided into two classes: (1) those malleable at a red heat, and (2) those which can be worked into the desired form only by casting.

The malleable alloys are composed almost entirely of cobalt and chromium, varying from 10 to 50 percent chromium with a corresponding cobalt composition. These alloys, which are resistant to nearly all forms of corrosion except hydrochloric, sulphuric or hydrofluoric acids, are used for tableware, surgical instruments, chemical and laboratory apparatus and jewelry. Patent specifications Nos. 873, 745 and 873,746, dated December 17, 1907, describe the methods of manufacture of these alloys and give the uses and properties of alloys of various compositions. Patent No. 1,150,113 dated August 17, 1915, describes similar alloys using iron as a third constituent.

The cast alloys are either ternary alloys of cobalt, chromium and tungsten or molybdenum; or quaternary alloys of cobalt, chromium, tungsten and molybdenum. The compositions and manufacturing methods of these alloys are described in patent specifications Nos. 1,057,423 and 1,057,828 dated April 1, 1913.

Stellite for tools may be obtained from the Haynes Stellite Company, Kokomo, Ind.

Another alloy of similar type is Cooperite. The patent specifications call for the following composition: ziroconium, 8-15%; nickel, 50% or more; no iron or carbon. Its cutting efficiency is not quite as high as that of stellite.

IX. REFERENCES. The principal references on high speed steel are as follows:

Taylor, F. W., "On the Art of Cutting Metals" an address made before the Am. Soc. of Mechanical Engineers, Dec., 1906, published by the Society.

Becker, O. M., "High Speed Steel", McGraw-Hill Book Company, 1910.

Edwards, C. A. & Kikkawa, H., "The Effect of Chromium and Tungsten upon the Hardening and Tempering of High Speed Tool Steel", Jour. Iron and Steel Inst., 92; 6 (1915).

Hibbard, H. D., "Manufacture and Uses of Alloys Steels", Bureau of Mines, Bull. No. 100, 1916.

Bellis & Hardy, "Notes on the Treatment of High-Speed Tool Steel", Trans. A.I.M.M.E., 56:496 (1917).

Mathews, J. A., "Modern High Speed Steel", Proc. A.S.T.M., 19:141 (1919). See also discussion of this paper.

Andrew & Green, "The Manufacture and Working of High-Speed Steel", Jour. Iron and Steel Inst. 99:309 (19[illegible]).